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OFF-LINE TESTING OF ALTERNATIVE OF INDUSTRIAL LUBRICANTS AND DIFFERENT TOOL MATERIALS FOR COLD ROLLING OF STAINLESS STEEL

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ABSTRACT

The present study tests different roll materials and lubricants for cold rolling, using a strip reduction test equipment at The Technical University of Denmark. Aims was to study the roll/tool material wear resistance and the resistance towards galling, i.e. lubricant film breakdown causing pick-up of work piece material on the roll surface and subsequent scoring of work piece surfaces. The four industrial lubricants investigated all consisted of mineral oil with fatty acid additives. The work piece material was stainless steel, AISI 304. The materials tested were NARVA 12B from Åkers, using the cold work tool steel SVERKER 3 from Uddeholm (AISI D2), SUPRA 3 from Åkers using the PM tool steel VANADIS 23 from Uddeholm and Åkers special finely distributed carbides and nitrides tested roll material, using an anti-seizure PM tool steel VANCRON 40. Evaluation of resistance to wear was done; during 20 % strip reduction NARVA 12B/SVERKER 3 showed a low surface roughness when lubricant "A" was used and during both 10 % and 20 % strip reduction VANCRON 40 showed a low surface roughness when lubricant "C" was used. Together with the lubrication the surface topography of the roll material is expected to influence friction. Evaluation of resistance to galling was done. Results showed VANCRON 40 to be especially prone towards galling.

KEYWORDS

Strip reduction test, work rolls, lubrication, surface roughness, galling, VANCRON 40, NARVA 12B, SVERKER 3, SUPRA 3, VANADIS 23

INTRODUCTION

The need for cold rolled strips is increasing and the quality issues such as the strip shape and surface quality become more and more concerned. Work rolls used in rolling mills play a significant role on the final strip quality. To achieve those goals, steel industries need to use work rolls that give the best possible surface roughness, shape, low friction, and low roll wear. In cold rolling, the surface of the work roll is subjected to high pressure, friction and thermal stress. The life of a cold work roll is limited by the deterioration of the surface finish due to wear through fatigue-based mechanisms, which means that the roll material must be hardened correctly to own good ductility and wear resistance [1].

Åkers AB produces rolls for a range of cold work applications, among others for cold rolling of thin sheet stainless steel that demands high surface quality. In those roll applications here presented Åkers uses tool material from Uddeholms AB. Åkers heat treats, turns, machines and grinds the tool material to rolls. The evaluation of three Åkers work roll products will be presented in this report; two work toll types produced by means of powder metallurgy VANCRON 40 and SUPRA 3 (from VANADIS 23) and one work tool type produced by means of conventional casting technologies NARVA 12B (from SVERKER 3). "VANCRON 40" is still under development as roll material and has therefore not yet a brand name. The main purposes to develop those tool materials are to achieve good surface finish of the rolled products.

The main challenges in cold rolling of stainless steels are:

- Roll wear, abrasive or adhesive, related to the rolling operation, the work material and the friction forces due to sliding contact between the work roll and the strip.
- Galling or “pick-up”, which is a result of heavy friction forces due to the sliding contact and the adhesive nature of the work material, Fig. 1. The galling mechanism is closely related to adhesive wear.
- Plastic deformation, which appears when the operating stress level exceeds the compressible yield strength (hardness) of the work roll material.

In this project, three proposed roll materials were studied. The study was conducted with respect to roll wear, surface quality and galling, in terms of adhesive wear and the tool materials resistance toward galling. Laboratory experiment was conducted and the results were analysed.

The three proposed Åkers roll materials are in more detail:

- VANCRON 40, a nitride powder metal tool steel
- NARVA 12B using SVERKER 3 (AISI D2) , a high-carbon, high-chromium tool steel alloyed with Tungsten
- SUPRA 3 using VANADIS 23 (AISI M 3:2) a Chromium-molybdenum tungsten-vanadium alloyed high speed steel

Tool materials characteristics, physical and chemical properties and recommended heat-treating process, by manufacturer, were described [2, 3]. Concerning roll material SUPRA 3 which was used currently as work roll in industrial operation, was used as reference material.
Experimental tests were performed to investigate wear, galling and surface finish. The objectives of the tests were to estimate the critical sliding length for onset of galling in strip reduction of stainless steel AISI 304, Fig. 2. Four different mineral based lubricants were used.

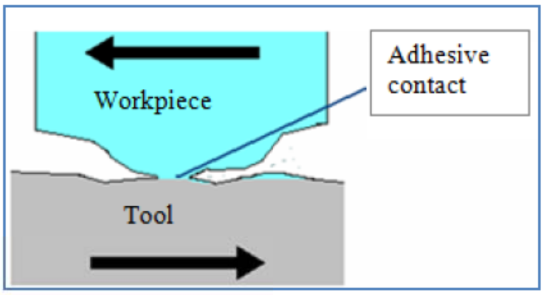


Fig. 1: Schematic illustration of adhesive wear

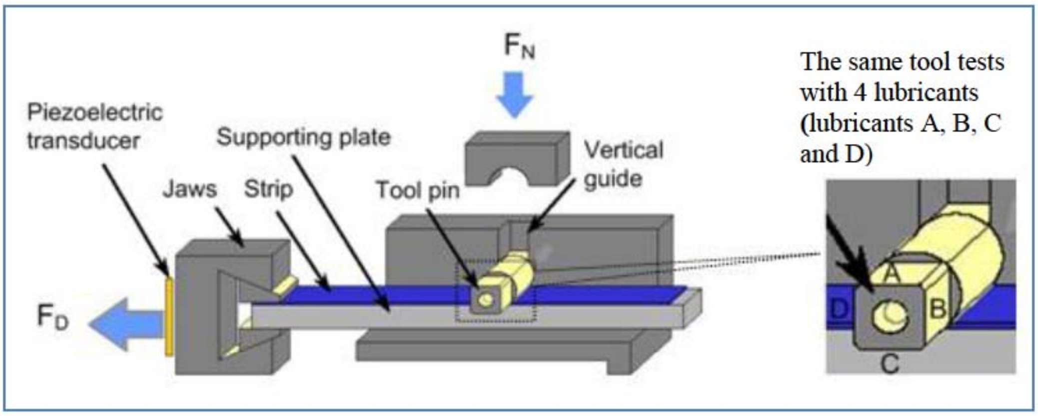


Fig. 2: Strip reduction test

Evaluation of tool material VANCRON 40 with regard to wear, surface quality and galling has also been conducted in the earlier study, in pilot rolling mill [2]. The pilot experimental resulted superiority result for VANCRON 40 evaluating surface roughness, galling and roll material hardness, compared to the reference material VANADIS 23 [2].

1. TYPES AND CHARACTERISTICS OF WORK TOOL MATERIALS

Chemical compositions of VANCRON 40, NARVA 12B/SVERKER 3 and SUPRA 3/VANADIS 23 are shown in Table 1 [3, 4]. As shown in the table, VANCRON 40 has been designed to have a dense distribution of small vanadium rich nitro carbides and a few molybdenum rich carbides in martensitic matrix. The chemistry insert vanadium rich nitro carbides phase exhibits a very low friction coefficient and very good tribological properties compared to MC, M_6C and M_7C_3 [5].

Table 1: Åkers and Uddeholm's product range of tool steels suitable for cold work applications [3, 4, 5]

Roll grade	Steel grade	Type of metallurgy	Chemical composition (weight %)							
			% C	% N	% Si	% Mn	% Cr	% Mo	% W	% V
VANCRON 40	VANCRON 40	Powder metallurgy	1.1	1.8	0.50	0.40	4.50	3.20	3.70	8.50
NARVA 12B	SVERKER 3	Conventional	2.05	-	0.30	0.80	12.70	-	1.10	-
SUPRA 3	VANADIS 23	Powder metallurgy	1.28	-	0.50	0.30	4.20	5.00	6.40	3.10

Due to its chemical and physical properties, VANCRON 40 is believed to be the best solution to resist adhesive wear and galling in the cold rolling process that require higher precision. However, this roll application is still under development. If successfully developed, the advantages predicted– a good wear and galling resistance-together with good grinding conditions will make this roll material competitive, compared to other type of work rolls that require higher precision, among others in cold rolling of thin stainless steel, which required high surface finish quality.

1.1 VANCRON 40

VANCRON 40 is as mentioned a nitride powder tool steel, which means that a "surface coating" is already integrated into the finished roll material. That principle gives suitable surface topography and a friction condition during rolling without the demand to introduce a real surface coating with

anti-galling properties. The result is a roll surface with very low friction that reduces galling or sticking of soft work materials [3, 4, 6, 7]. In cold rolling applications of stainless steels and mild steels, galling and adhesive wear are often the dominating tooling problems, see Fig. 3a and b. This could also be the case in powder compacting of different work materials.
As mentioned using VANCRON 40 as a roll material offers the possibility of eliminating the both time- and cost-consuming surface coatings. This is achieved in the manufacturing process of VANCRON 40 by introducing an extra nitride operation. This step is still under development.

Fig. 3a: Adhesive wear [6]

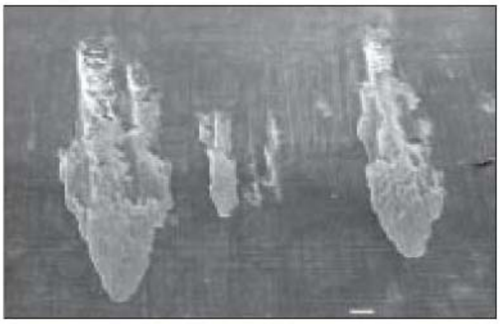


Fig. 3b: Galling [6]

1.2 NARVA 12B

NARVA 12B is a roll type from a high-carbon, high-chromium tool steel alloyed with tungsten, SVERKER 3, characterized by [8]:

- Highest wear resistance
- High compressive strength
- High surface hardness after hardening
- Good through-hardening properties
- Good stability in hardening
- Good resistance to tempering-back

NARVA 12B is used successfully in cold rolling applications of stainless steels because of its wear resistance, high compressive strength and high surface hardness after hardening. As tool material SVERKER 3 has gained widespread acceptance as steel with exceptional wear resistance, suitable for long-life tooling with low repair and maintenance costs, for maximum production economy [6].

1.3 SUPRA 3

SUPRA 3 which is used as roll grade reference in this project is a high alloyed powder metallurgical high speed steel corresponding to the material AISI M3:2 with a very good abrasive wear resistance in combination with compressive strength. It is suitable for demanding cold work applications like blanking of harder materials like carbon steel or cold rolled strips and cutting tools. The machinability and grinding are superior than for conventional high speed steel and so is the dimensional stability after heat treatment [8].
SUPRA 3 is used successfully in cold rolling applications of stainless steels because of its wear resistance and toughness.

2. LABORATORY EXPERIMENT, STRIP REDUCTION TEST

The purpose of the experimental test in "strip reduction test", see Fig. 2, was to study the depth profiles of the ironed stainless steel strips, emergence of galling and to study the lubrication performance used by steel industries. Due to the ironing process exposed to very high pressure in contact area, the commonly used lubricants for ironing process of stainless steel strips are lubricants with extreme pressure additives. In a previous work and with the same experimental device the nature of the extreme pressure (EP) effect of the dialkylpolysulfides and chlorinated paraffin during the ironing of stainless steel AISI 304 has been studied [9].
Strip reduction tests, in which chlorinated paraffin and dialkylsulfide were compared as EP-additives, have shown significantly stronger EP-effect of the chlorine containing lubricant, than for the sulphur containing lubricant. The better lubrication performance demonstrated by chlorinated paraffin compared to dialkylpolysulfides was attributed to the chemical activity of the chlorinated paraffin with all the main components of stainless steel [9].
In a similar way, pick-up and galling due to lubricant film breakdown is a severe limitation in cold forming of tribological difficult metals like stainless steel was studied. Chlorinated paraffin containing EP-additives was used [10].
The galling evaluation equipment here used, is developed by The Technical University of Denmark, DTU, previous used in some research projects; among others in testing of friction and lubrication in bulk metal forming, lubricant test methods for sheet metal forming, quantitative evaluation of lubricants and tool surfaces for ironing of stainless steel and prediction of limits of lubrication in strip reduction testing [10-13].
For this project, the objectives of examining roll materials in strip reduction test were to examine scratch of the strip, galling and surface roughness of the roll materials under severe tribological conditions. The critical sliding length for onset of galling in strip reduction was estimated for stainless steel with four different lubricants. Test principles of the strip reduction test is a simulative test where the process conditions in typical ironing operations can be varied and their effects on mainly the tribology of the deformed work piece can be studied in a controlled manner.
A schematic of the test is shown in Fig. 2. The metal strip work piece is reduced in thickness by a non-rotating cylindrical tool held in place by vertical guides. The tool is fixed with a defined displacement into the strip and the strip is then reduced in thickness by pulling the strip and support plate as shown in the figure. The normal pressure and pulling speed is held constant throughout the test but the temperature will increase due to friction and plastic deformation. Depending on the tribological properties of the chosen lubricant, tool material, tool hardness, the tool might experience cold welding of work piece material to the tool with subsequent scratching of the strip surface. This phenomena of cold welding of work piece material to the tool and scratching of the subsequent work piece surface is known as galling and is a severe problem in industry leading to poor product quality and at worst tool failure.
By measuring the threshold sliding length of the strip before the onset of galling where the first scratches appear on the strip surface it is possible to compare the performance of different lubricants and/or work piece and tool materials. The onset of galling can often be estimated by visual inspection but a more precise method is to measure roughness profiles across the strip width at regular intervals. Scratches due to galling can then easily be identified and the sliding length determined. Fig. 4 shows an example of appearance of the scratches at a sliding length of 270 mm. Galling is typically a progressive effect that when initiated will escalate fast due to local pick-up on the tool surface and high temperatures leading to a continuous increase in galling, as observed in the figure.
In the present project, before application of lubricant, the tool and strip are cleaned using petroleum ether. The lubrication is applied using a pipette and distributing in an even layer by fingers. After the test the strips are cleaned and the thickness is measured in order to verify the actual reduction of the strip.

The roughness of the strips is then measured across the strip width – i.e. orthogonal to the drawing direction hereby registering any scratches due to galling. The number of scratches deeper than 1µm (N_{ri}) and deeper than 2 µm ($N_{ri,2}$) compared to the average height is counted automatically in the software and is saved along with several other roughness parameters. These parameters can then be plotted versus the sliding length giving a clear idea of the performance of the different lubricants.

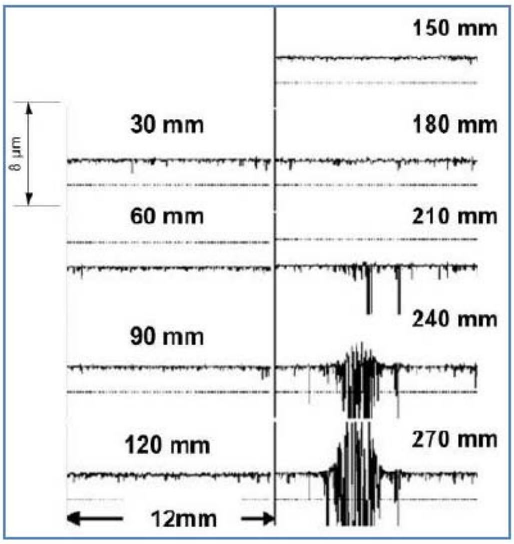


Fig. 4: Typical measurement of roughness profiles across the strip width at regular intervals [10]

The following experimental conditions were applied:

Work piece/strip

- Material: Stainless steel, 304
- Dimensions: 0.7x15x500 mm

Lubricants (4 types)

- A: Mineral oil with additives of fatty acids, high viscosity
- B: Mineral oil with Ester and EP additives, lower viscosity than A
- C: Mineral oil with Ester and EP additives, lower viscosity than A and B (C has another type of concentration than A and B)
- D: Mineral oil with additives of fatty acids, high viscosity

Process parameters

- Reduction, r: 10-20 %
- Temperature: Room temperature, 20 degrees C
- Average sliding speed: 80 mm/s
- Surface roughness of tool materials, R_a: 20 µm
- Two hydraulic cylinders with a max. force of 5 kN each
- The max. sliding length: about 300 mm

3. RESULTS AND DISCUSSION

The strip reduction test is a simulative test where the process conditions in typical ironing operations can be varied and their effects on mainly the tribology of the deformed strip can be

studied in a controlled manner. Ironing refers to the process of uniformly thinning the work piece. As shown in Fig. 2, the same tool material with its 4 faces -A, B, C and D- was used in evaluation of 4 types of lubricants. Due to severe process conditions, the process needs lubricants with an extremely high load bearing capacity. A normal used lubricant at DTU is chlorinated paraffin oil [11].
Considering the capacity of the test device and the type of lubricants, the maximum reduction which could be accomplished was 20 %. For that reason, 10 % and 20 % reductions were proposed for the present experiment. As the maximum sliding length of the strip reduction test is about 210 mm with 7 sliding lengths; 30, 60, 90, 120, 150, 180 and 210 mm, for each strip with four types of lubricants were proposed to obtain better evaluations of the lubricant load bearing capacity, galling and surface roughness of the strip, see Fig. 5.
The reason of taking several sliding lengths is to help analysing initiation and progress of galling in the sliding length range. Unfortunately, due to severe process conditions and not using an extremely high load bearing capacity, like chlorinated paraffin oil, the initiation and progress of galling was observed in the early sliding length range 10 and 30 mm. The reason for that is that the industrial recommended lubricants don't use or allow chlorinated paraffin oil in the rolling operations. Despite those challenges, the experiments in "the strip reduction test" are believed to give some indication about galling.
The initial strip thickness is t_0 (0.7 mm) and the final strip thickness is t_1. Lubricant breakdown in strip reduction is identified as scoring of the sheet surface resulting in distinct scratches in the surface. The scratches are visible even when very small, because the ironed surface prior to lubricant breakdown appears very smooth and shiny due to contact with the polished tool surface with a roughness of R_a 0.20 µm. The limit of lubrication in the strip reduction test is defined as the threshold drawing length before onset of galling, which has been determined for each combination of reduction and tool at room temperature by evaluating the results of four identical tests.
Similar tests were also conducted by N. Bay et al. [12] for prediction of limits of lubrication in strip reduction testing. Their work described a method of combined experimental and numerical analysis to quantify the limits of lubrication in a dedicated simulative strip reduction test. The limit of lubrication is quantified as the threshold drawing length before galling occurs.
As the main surface roughness parameters of industrial interest in evaluation of roll or tool wear and surface quality and galling are R_a, R_z, the number of scratches deeper than 1 µm (N_{ri}) and deeper than 2 µm (N_{r2}), are compared to the average height which is counted automatically in the software and is saved along with several other roughness parameters. N_r describes as the number of valleys deeper than the limited μm. Using roughness checker device, up to 7 parameters could be calculated, among others R_a, R_{sk}, R_z, R_t, R_p, R_{zmax}. To help galling evaluation, the system integrated some other parameters to the average height is counted automatically in the software and is saved along with several other roughness parameters.

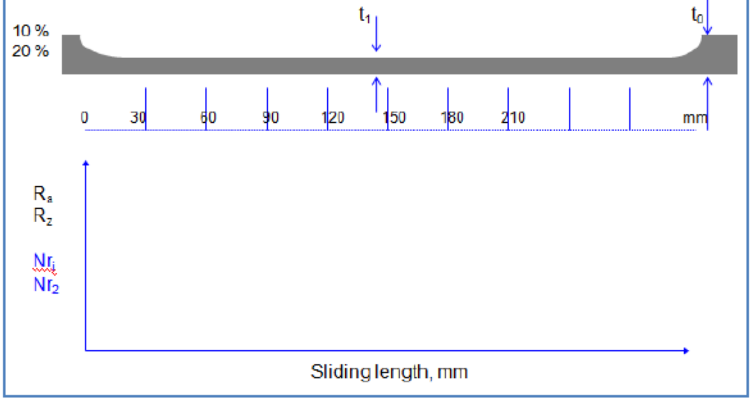


Fig. 5: Principles of the strip measurement with 7 sliding lengths and 2 reductions, Nr_1: Number of valleys deeper than 0.5 µm (Nr_1's), Nr_2: Number of valleys deeper than 0.5 µm (Nr_1's)

3.1 Evaluation of surface roughness R_a and R_z

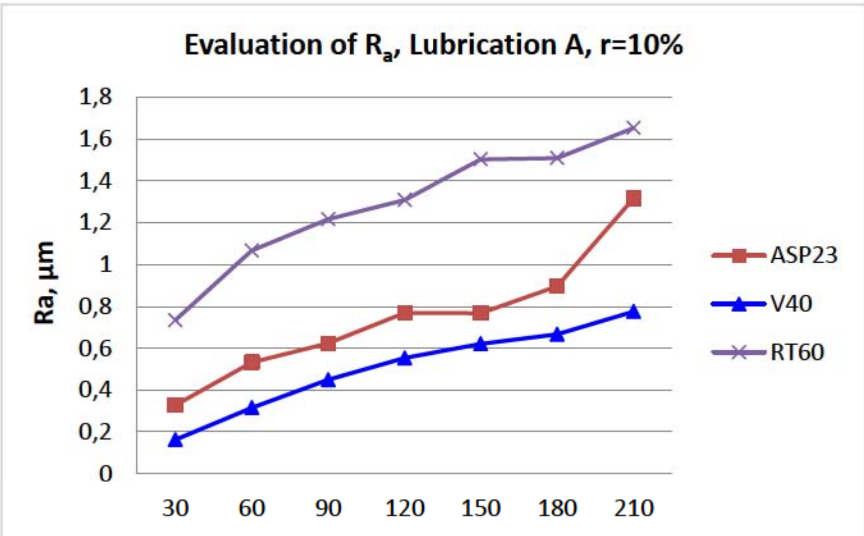
The practical industrial parameters; R_a, R_z and N_{r2} were evaluated. Fig. 6 shows the evaluation of R_a for two reductions, r = 10 and 20 %. The measurement is done for lubricant A where x-axis stands for sliding length. The materials, VANCRON 40, SVERKER 3 in the roll grade NARVA 12B and VANADIS 23 in the roll grade SUPRA 3, were evaluated.

As shown in the figure, VANCRON 40 shows low and stable R_a in low reduction (r=10 %). In addition, VANCRON 40, with its internal surface coating characteristic shows high "bearing capacity", or in other words a self-lubricating characteristics, with increasing of sliding length, this is a non-progressive effect.

Despite the sliding length and the increasing of scratches, the figure shows also that the slope of the curve of VANCRON 40 staying stable (low interval, 0.6 μm). The argument is valid for both low and high reductions.

SVERKER 3, despite good bearing capacity and stable characteristics (with interval of about 1.0 μm), the R_a measurement for low and high reductions was not stable. In case of VANADIS 23, R_a deteriorates quickly with increasing of sliding length. That tendency show, indirectly, the increasing of galling is higher in VANADIS 23 than in VANCRON 40 or SVERKER 3.

The comparison of R_a for VANCRON 40 and VANADIS 23, for all four lubricates, is shown in Fig. 7, where the solid lines represents VANCRON 40 and the dotted lines represents VANADIS 23. As shown in the figure, the slopes of VANCRON 40 curves remains stable with interval between low and high sliding length (30 and 150 mm), while the slopes of VANADIS 23 is increasing quickly with increasing sliding length, with high interval between the low and high sliding length (30 and 150 mm). Those tendencies can be described as the VANCRON 40 tool ability to remain unaffected with increasing of sliding length, or as VANCRON 40 high resistance toward adhesive wear, under severe conditions.



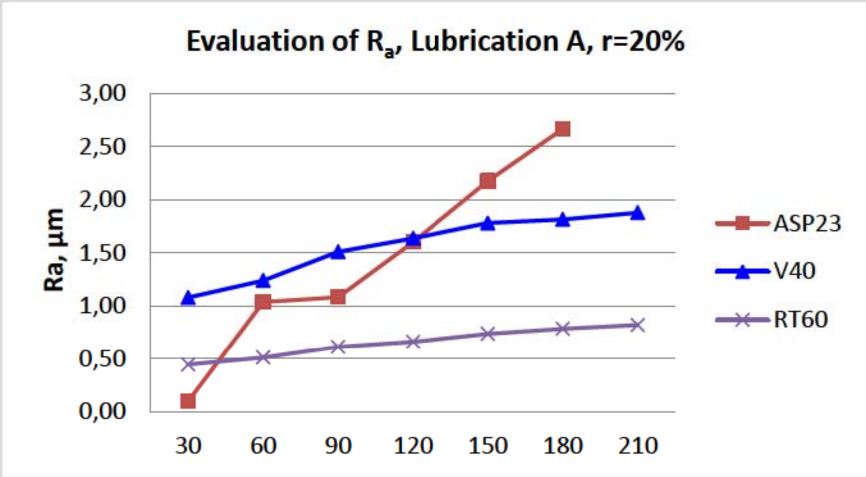


Fig. 6: Evaluation of Ra for reduction, r= 10 and 20 % with lubricant A. x-axis is the sliding length in mm. V40: VANCRON 40, RT60: SVERKER 3 and ASP23: VANADIS 23

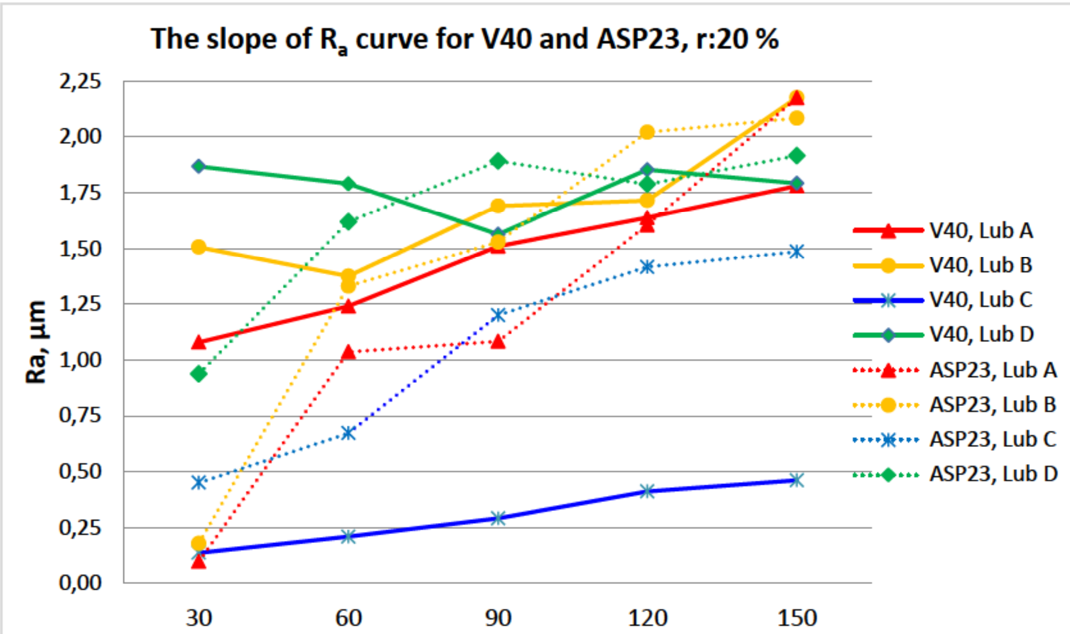


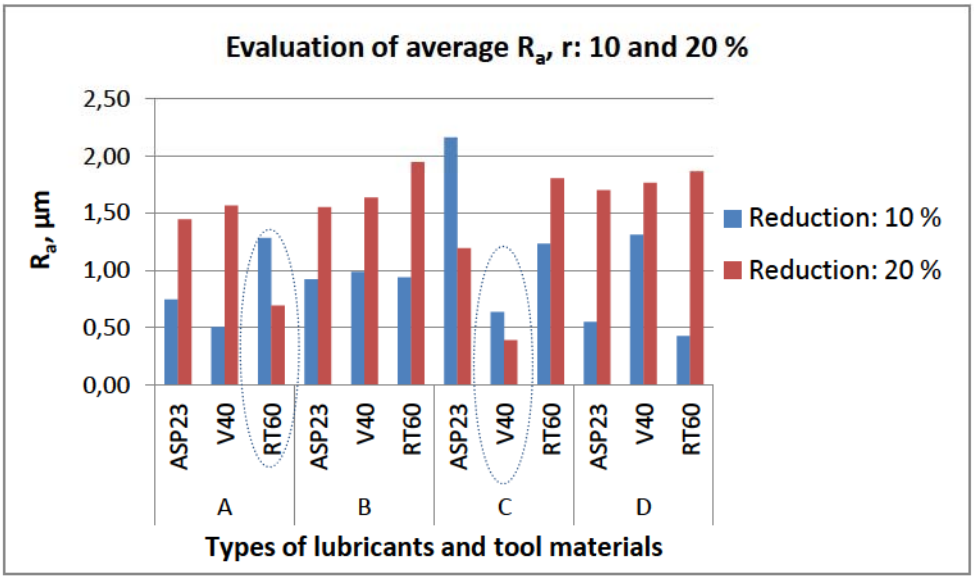
Fig. 7: The slope of Ra curve of VANCRON 40 for reduction 20 % with 4 different lubricants. Sliding length 30 to 150 mm. V40: VANCRON 40, ASP23: VANADIS 23

In a similar manner, evaluation of R_z for reduction, r = 10 and 20 % with lubricant A was conducted, see Fig. 8, and similar results, as R_a, were observed. To simplify the evaluation of R_a and R_z, for reductions 10 and 20 % with four proposed lubricants and three tool materials, average value of R_a and R_z was chosen.

As shown in the Fig. 8, VANCRON 40 in combination with lubricant C gave very low R_a and R_z for both low and high reductions. Lubricant C is a mineral oil with Ester and EP additives and a lower viscosity. See dotted area indicated in Fig.8.

Lubricates A, B and D show similar tendency for all three tool materials; with lower R_a and R_z for lower reduction (10 %) and higher R_a and R_z for higher reduction (20 %).

Some other good results with low roughness were also observed for SVERKER 3 and lubricant A. Lubricant A is a mineral oil with additives of fatty acids and a high viscosity. See the dotted area indicated in Fig.8.



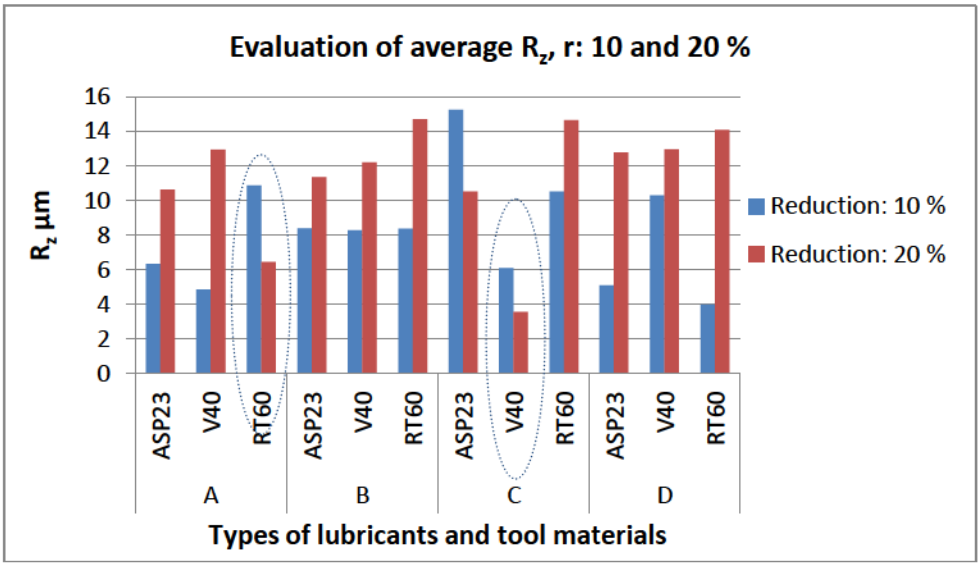


Fig. 8: Evaluation of average R_a and R_z for reduction, r= 10 and 20 % for 4 types of lubricants and three tool materials. V40: VANCRON 40, RT60: SVERKER 3 and ASP23: VANADIS 23

3.2 Evaluation of surface roughness, galling, N_{r2}

Normal used lubricants in cold rolling mills are mineral based, emulsion and water-based synthetic lubricants. As mentioned before, evaluation of galling by using “strip reduction test” was more appropriate with the use of chlorinated paraffin as lubricant but the proposed lubricants in this project were lubricants A, B, C and D, mineral based lubricants with lower EP additives. Due to that reason, the evaluation of galling scaled-up to higher number of scratches deeper than limited values. This logic is believed to give some hints about the tool materials ability to resist scratches and adhesive wear.

Fig. 9 shows the evaluation of galling (N_{r2}, number of valleys deeper than the limited value for galling) for reductions, *r*: 10 and 20 %. The figure shows the result of using lubricants A, B, C and

D for the 3 roll materials. As shown in the figure, N_{r2} of VANCRON 40 remains lower with the use of lubricants B, C and D. The results also show that N_{r2} of VANCRON 40 is not affected much with increasing of reduction from 10 to 20 %, which shows that the influence of reduction is not restricted in case of VANCRON 40, spec. in using lubricants C and D.

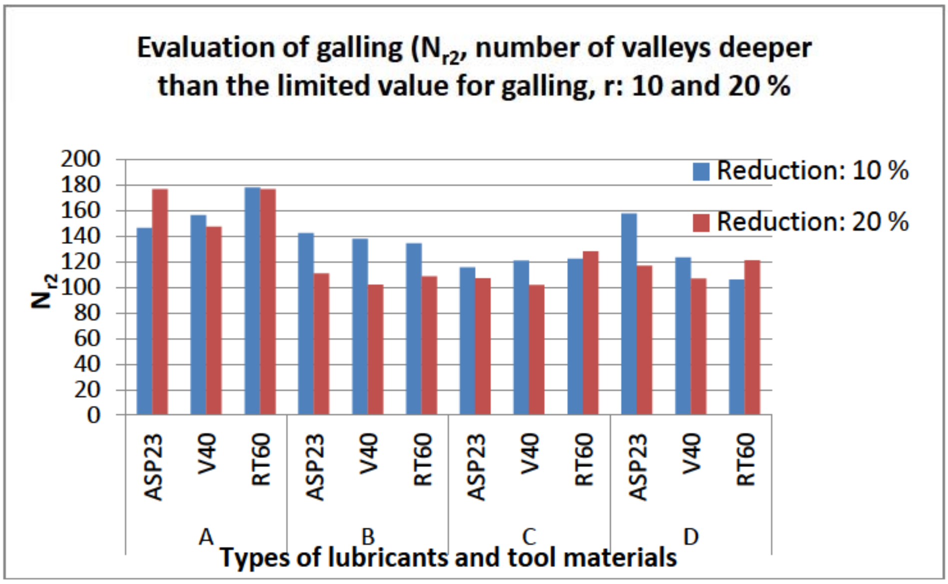


Fig. 9: Evaluation of galling, N_{r2}, for reductions, r= 10 and 20 % and lubricants A, B, C and D. V40: VANCRON 40, RT60: SVERKER 3 and ASP23: VANADIS 23

4. CONCLUSIONS

Using different tribological conditions, with the help of a strip reduction test equipment developed at the Technical University of Denmark, DTU, some roll materials for cold rolling applications and lubricants were evaluated. The evaluation was concentrated to roll wear, surface quality and galling.

Three roll materials have been evaluated, together with four lubricants. Åkers uses tool material from Uddeholms AB that is heat treat, turned, machined and grinded to rolls. The roll material "VANCRON 40" is still under development by Åkers using the tool material VANCRON 40 from Uddeholm.
Results showed that VANCRON 40 is especially prone towards galling. The progressive effect and the escalation of local pick-up when testing the roll material VANCRON 40 was significantly smaller in comparison to the roll material NARVA 12B from the tool SVERKER 3 and when testing the roll material SUPRA 3 using the tool material VANADIS 23.
The reason proposed for the galling results is the VANCRON 40 properties. VANCRON 40 is as mentioned a nitride powder tool steel, which means that a "surface coating" is already integrated into the finished roll material. That principle gives suitable surface topography and a friction condition during rolling without the demand to introduce a real surface coating with anti-galling properties.
Evaluation of resistance to wear was done by measuring the surface roughness. During 20 % strip reduction NARVA 12B/SVERKER 3 showed a low surface roughness when lubricant A was used, but not when lubricant B, C or D was used. Lubricant A is a mineral oil with additives of fatty acids and a high viscosity. Furthermore; during both 10 % and 20 % reduction when lubricant C was used VANCRON 40 showed a low surface roughness, but not when lubricant A was used. Lubricant C is

a mineral oil with Ester and EP additives and a lower viscosity. For VANCRON 40, when the remaining lubricants B and D were used, the roughness was lower or in line with the other materials tested.

So, the lubricants used have a strong influence on the results. In addition to the lubrication the surface topography of the roll material influences friction, not only dependent of the first grinding and polishing treatment, but more important is the microstructure of the roll, meeting the strip surface, then in terms of type of carbides, size of carbides e t c. As an example, the carbon-nitrides rich material VANCRON 40 is expected to give a consistent surface topography during rolling with a low resulting roughness.

This study shows that the roll material VANCRON 40 has proven to give some promising results, and when fully developed, this roll material is believed to be able to strongly compete.

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